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The effects of 3-D Screw on the Nasomaxillary Complex in Skeletal Class III Malocclusion: A FEM Analysis

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***Abstract*---**Aim of the study is to evaluate the Stress distribution and displacement of various structures of nasomaxillary complex with 3-D screw in skeletal class III malocclusion. An analytical model was developed from a human skull of a 15-year-old male. CT scan images of the skull were taken in axial direction parallel to the F-H plane, which was processed using Mimics software, required portion of the skull & 3-D screw appliance was converted into geometric model using reverse engineering technique. ANSYS software was used to solve the mathematical equation. Contour plots of the displacement and stresses were obtained from the results of the analysis performed. Maximum transverse displacement was 3.18mm at the permanent

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first maxillary teeth. Maximum antero-posterior displacement was 1.26mm at the anterior part of zygomatic bone and 1.35mm of displacement frontozygomatic suture. Maximum vertical displacement was 2.81 mm representing the inferior and medial portion of the nasal bone and indicating downward displacement. Pyramidal displacement of maxilla was evident. Apex of pyramid faced towards nasal bone and base was located on the oral side. There was downward, forward movement of maxilla with a tendency toward posterior rotation. Maximum von Mises stresses were found along midpalatal, zygomaticomaxillary, nasomaxillary, frontozygomatic sutures.

***Keywords*---**finite element method, 3D screw, displacement, stress, nasomaxillary complex.

Introduction

Transverse discrepancy is a common problem that is more commonly found in skeletal class III malocclusion[1].This is not only due to an underdeveloped maxilla and an overdeveloped mandible with a low tongue posture, which results in an absolute transverse and sagittal discrepancy[2]. Maxillary transverse expansion is the treatment of choice for these patients. To treat transverse discrepancy slow and rapid maxillary expansions are used. Jackscrew and hyrax like devices are used to apply orthopaedic force to split the Midpalatal suture, separating the two maxillary halves to produce lateral displacement in growing and young adult individuals respectively. In adults with heavily interdigitated and fused mid-palatal suture, the splitting becomes difficult or almost impossible, so prior to placing RME appliance the suture was split using Surgically Assisted Rapid Palatal Expansion[3]. Conventional RPE provokes an orthodontic effect of buccal tipping and movement of the posterior teeth. To overcome this issues MARPE was developed. But none of this expansion devices can be used to treat transverse as well as sagittal discrepancy simultaneously. So, to treat transverse as well as sagittal discrepancy simultaneously in the growing individual 3-D screw like slow expansion device is used, which provides independently controlled movements.
In recent years, finite element method (FEM) has been a powerful research tool for solving various structural mechanical problems. It is recognized as a general procedure for mechanical approximation to all physical problems that can be modeled by differential equation description. In the literature, many analysis were conducted to study the stress distribution of these type of palatal expansion appliances and its effect on the craniofacial complex. But not even single study is done on the 3-Dimentions screw and its effect on nasomaxillary complex. So, the aim of the study was to evaluate the Stress distribution and displacement of various structures of nasomaxillary complex with 3- D screw in skeletal class III malocclusion.

Material and Method

The computed tomography (CT) of a 15-year-old male with skeletal Class-III patient is obtained. The Spiral CT scanning was performed. The Spiral CT was used to generate the three-dimensional (3D) model for the finite element analysis

(FEA) in the study. In addition, the 3D skull image was trimmed to exclude the mandible. The CT scan of a Class-III patient is procured and then are converted the dicom data into geometric models using reverse engineering technique. Reverse engineering includes scanning the models, measuring the length, diameter and other features using standard measuring instruments and scanning machines. Geometric modeling was made using “Rapid form” software. Geometric model consists of only surface data of the skull. Then geometric models of the skull including all the teeth are then imported into the meshing software "Hypermesh". In Hypermesh the individual parts like bones, sutures, teeth, PDL are then discretized (meshing) and assembled (Fig. 1). Expansion appliances like 3-D screws and blocks, Wires are also modeled using reverse engineering method and placed on to the maxilla (Fig. 1). Meshed model is called finite element model and it consists of node and element data. The material properties (Young’s modulus and Poisson’s ratio) of the tooth, cortical bone, and PDL (periodontal ligament), cancellous bone, sutures were entered in the pre-processing stage. The assembled finite element model of the skull, tooth, and PDL was then imported into ANSYS software for analysis. ANSYS software was used to solve the mathematical equation and to calculate the stress and displacement pattern of the skull by giving 3 turns to the 3-D screw. Post processing was the last stage of the FEM in which contour plots of the displacement and stresses was obtained from the results of the analysis performed.

Result

ANSYS 2017.2 Software is used to simulate the model. Stress is measured in “MPa” and displacement is measured in “millimetre”. Directions to be followed in the model are as below: (1) X is transverse direction, +X is Right side and –X is left side movement. (2) Y is Anteroposterior direction, +Y is posterior and –Y is Anterior direction. (3) Z is Vertical direction, +Z is Upwards and –Z is downward movement. To see the effect of 3-D screw on the nasomaxillary complex in skeletal class III malocclusion, we had performed the FEM study so that the biomechanical changes were evaluated under the following headings:

1. Displacement of different bones and sutures of craniofacial complex
2. Stress distribution among different bones and sutures

The results of displacement patterns of various structures are shown in (Table 3).
Displacement In the X- direction (Occlusal View), total transverse expansion was 3.25 mm. In the Y-direction (Lateral View), total Anteroposterior expansion is -1.175mm. In Z- direction (Frontal View), in anterior region it moves upward by 2.8mm and in posterior region it moves downward by -1.175mm. Maxilla (Fig. 2, Table 3), In X-direction, there was 1.180 mm and -1.153mm of displacement of alveolar process of maxilla in relation to second molar, first molar region on right and left side respectively. So, total transverse displacement in maxilla was 2.33mm. In Y-direction, there was -0.818mm of anterior displacement of the alveolar process of the maxilla and 0.761 mm of posterior displacement of the nasal process of maxilla. In Z-direction, there was 2.79 mm of upward displacement of the zygomatic process of maxilla on right & left side. Minimal upward displacement of medial pterygoid plate (0.472 mm) was seen. Nasal Bone (Table 3), In X-direction, Total displacement in the nasal bone was 0.48mm. In Y-

direction, 0.999mm of posterior displacement was seen. In Z-direction, 2.81mm of upward displacement was seen. Zygomatic Bone (Table 3), 1.04mm of lateral displacement was observed in X-direction. posterior displacement was around 1.26mm in Y -direction. Upward displacement of around 2.54mm was observed in Z - direction. Midpalatal Suture (Table 3) had shown 0.374mm of transverse opening, 0.449mm of sagittal displacement and anteriorly it moved in upward direction, anteriorly by 2.04mm and posteriorly by 0.65mm. Frontonasal Suture (Table 3), maximum lateral displacement, posterior displacement and upward displacement of 0.287mm, 0.954mm of and 2.75mm were seen respectively. Frontozygomatic Suture (Table 3), 0.856mm of Maximum Lateral displacement, 1.35mm of posterior displacement and 2.45mm of upward displacement were seen. Internasal Suture (Table 3), 0.287mm of lateral displacement, 0.965mm of posterior displacement and 2.81mm of upward displacement. Nasomaxillary suture (Table 3), 0.551mm of lateral displacement, 0.999mm of posterior displacement and 2.76mm of upward displacement was seen. Zygomaticotemporal Suture (Table 3) 0.743mm of Lateral displacement, 0.304mm of posterior displacement and 1.88mm of upward displacement was seen. Pterygomaxillary Suture (Table 3) There was 1.76mm of total lateral displacement, 0.582mm of anterior displacement and 1.43mm of upward displacement seen. Zygomaticomaxillary suture (Table 3) 1.143mm of lateral displacement, 0.716mm of posterior displacement and 2.79mm of upward displacement was seen. Teeth (Table 3) Maximum 3.18mm of displacement was seen in intermolar region. And 1mm of displacement is seen between central incisors. -1.07mm of teeth displacement was seen on buccal side. 2.51mm of upward displacement was seen of all the teeth.

Stress Distribution in Maxilla (Table 4) Maximum von mises stress was 133.779MPa in the alveolar process of maxilla in relation to canine and first premolar region. Less stress distribution was seen in the palatal shelves as compared to alveolar process of the maxilla. In Nasal Bone (Table 4), Maximum von mises stress was 72.74MPa in the inferior portion of the nasal bone. And there was lesser amount of stress on right and left side of the nasal bone. In Zygomatic Bone (Table 4), Maximum von mises stress was 17.18MPa in the superior portion of the zygomatic bone. But it was negligible. Midpalatal Suture (Table 4), Maximum von mises stress was 2.65MPa in the anterior region. Compressive stress of around 0.053MPa was seen in posterior region. Frontonasal Suture (Table 4), Maximum Von-mises stress was around 1.57MPa in the frontonasal suture. Frontozygomatic Suture (Table 4), Maximum Von-mises stress was around 1.66MPa in frontozygomatic suture. Compressive stress of around 0.135MPa was observed. Internasal Suture (Table 4), Maximum Von-mises stress was around 0.653MPa in internasal suture. Nasomaxillary Suture (Table 4), Maximum Von-mises stress was around 2.9MPa in nasomaxillary region. Compressive stress of around 0.032MPa was observed. Zygomaticotemporal Suture (Table 4), Maximum Von-mises stress was around 1.25MPa in zygomaticotemporal region. Pterygomaxillary Suture (Table 4), Maximum Von-mises stress was around 0.782MPa in pterygomaxillary suture. Compressive stress of around 0.041MPa was observed. Zygomaticomaxillary Suture (Table 4), Maximum Von-mises stress was around 3.62MPa in zygomaticomaxillary suture. Compressive stress of around 0.65MPa was observed. Teeth (Table 4), Maximum Von-mises stress was around 126.85MPa on palatal surface of crown of the first

premolar mesially. 84.675MPa von mises stress was observed on palatal surface of crown of the canine distally and palatal surface of crown and CEJ region of first premolar. Alveolar Bone (Table 4), Maximum Von-mises stress was around 39.6MPain the anterior region.

Table 1
Young's Modulus and Poison's Ration of the skull material

Material	Young's modulus(kg/mm2)	Poison's ratio
Tooth	2.6×10^{3}	0.15
PDL	6.8×10^{-2}	0.49
Alveolar Bone	1.40×10^{3}	0.15
compact bone	1.37×10^{3}	0.3
Sutures	6.8×10^{-2}	0.49

Table 2
Number of nodes and elements

Material	No. of nodes	No. of elements
Teeth	13468	50131
PDL	4275	9031
Cancellous Bone	17044	85173
compact bone	10554	19888
Sutures	1032	1211
Adam's Clasp	2417	4543
3-D screw Appliance	4273	19280
Total	40387	187157

Table 3
Computational result of the transversal (X), sagittal (Y), and vertical (Z) displacements of the various skeletal structures of the craniofacial complex by giving 3 turns to the 3-D screw

Region	X (mm)	Y (mm)	Z (mm)
Midpalatal suture	0.374mm	0.449mm	Anteriorly 2.04mm upward Posterior 0.65mm
Frontonasal suture	0.287mm	0.954mm	2.75mm
Frontozygomatic suture	0.856mm	1.35mm	2.45mm
Internasal suture	0.287mm	0.965mm	2.81mm
Nasomaxillary suture	0.551mm	0.999mm	2.76mm
Zygomaticotemporal suture	0.743mm	0.304mm	1.88mm
Pterygomaxillary suture	1.76mm	0.582mm	1.43mm
Zygomaticomaxillary suture	1.143mm	0.716mm	2.79mm
Maxilla	2.33mm	0.818mm	2.79mm

Nasal bone	0.48mm	0.999mm	2.81mm
Zygomatic bone	1.04mm	1.26mm	2.54mm
Teeth	3.18mm	1.07mm	2.51mm
Full skull	3.25mm	1.175mm	Anteriorly moves upward by 2.8mm and posteriorly moves downward by 1.175mm

Table 4
Computational result of von Mises stress contours of the various skeletal structures

Bones	Max. VM stress (MPa)	Min. VM stress (MPa)
Maxilla	133.78MPa	0.349MPa
Nasal bone	72.74MPa	0.752MPa
Zygomatic bone	17.78MPa	0.089MPa
Alveolar bone of maxilla	39.6MPa	0.037MPa
Teeth	126.85MPa	0.325MPa
Midpalatal suture	2.65MPa	0.021MPa
Frontonasal suture	1.57MPa	0.198MPa
Frontozygomatic suture	1.66MPa	0.127MPa
Internasal suture	0.653MPa	0.287MPa
Nasomaxillary suture	2.9MPa	0.317MPa
Zygomaticotemporal suture	1.25MPa	0.481MPa
Pterygomaxillary suture	0.782MPa	0.058MPa
Zygomaticomaxillary suture	3.62MPa	0.102MPa

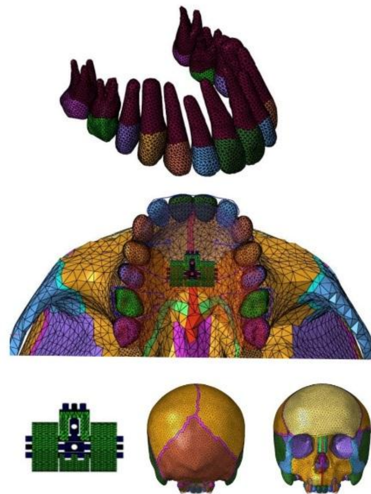

Figure 1. Finite Element Models with Nodes and Elements

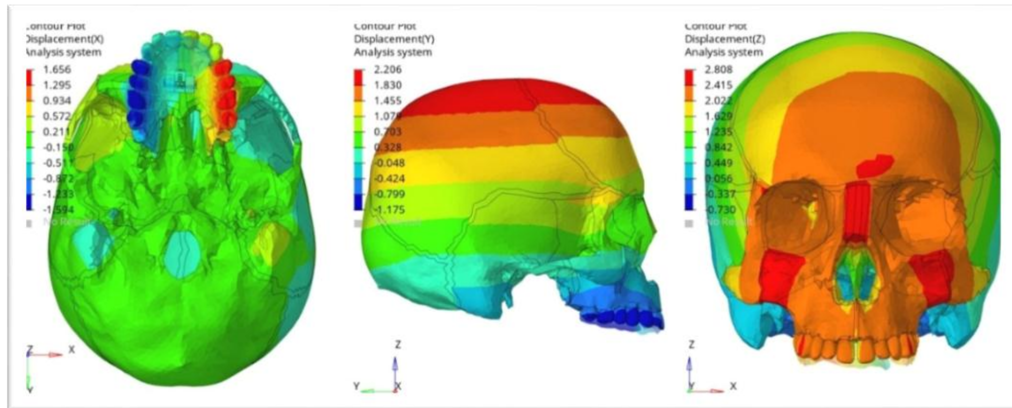

Figure 2. Displacement contours of the skull model in X, Y, Z direction

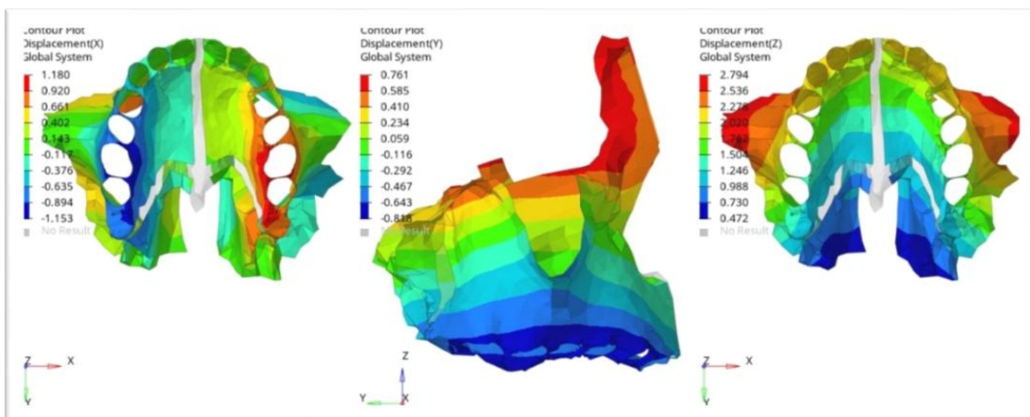

Figure 3. Displacement Contours of Maxilla in X, Y, Z Direction

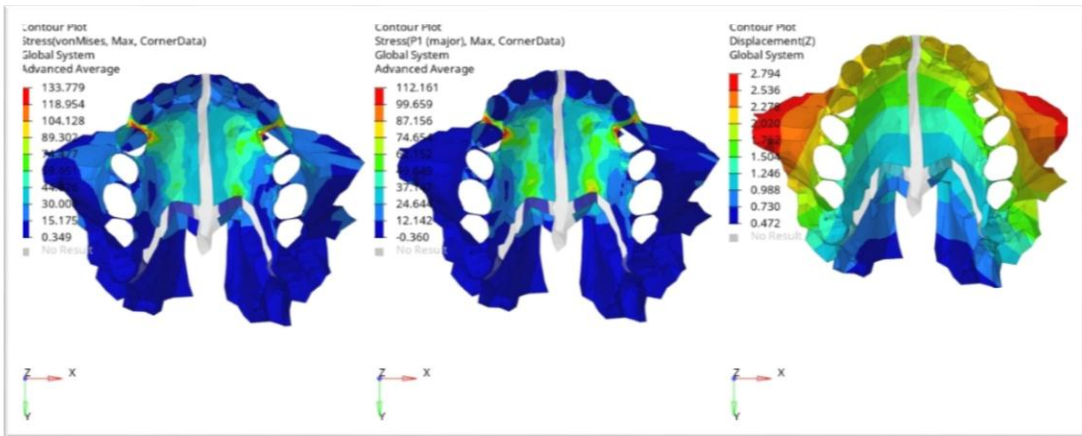

Figure 4. Stress Contours of Maxilla (Von-Mises Stress And Maximum Principal Stress)

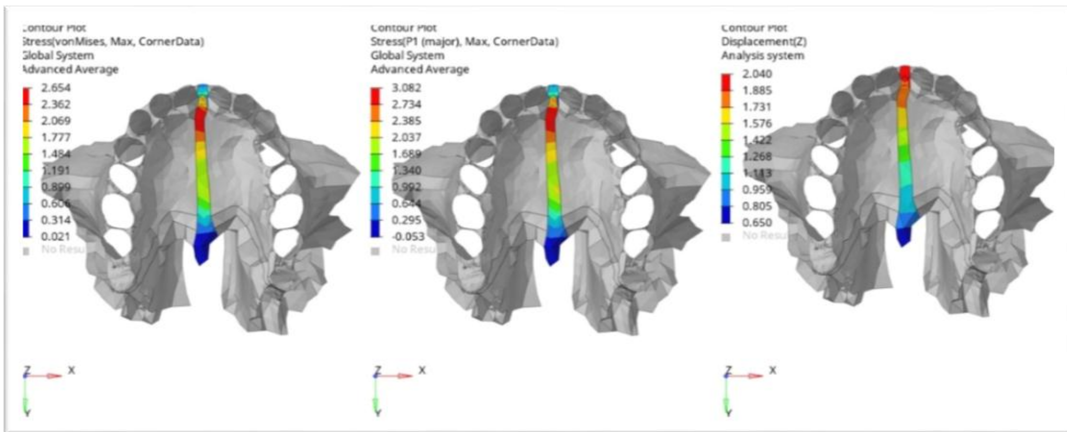

Figure 5. Stress Contours of Midpalatal Suture (Von-Mises Stress and Maximum Principal Stress)

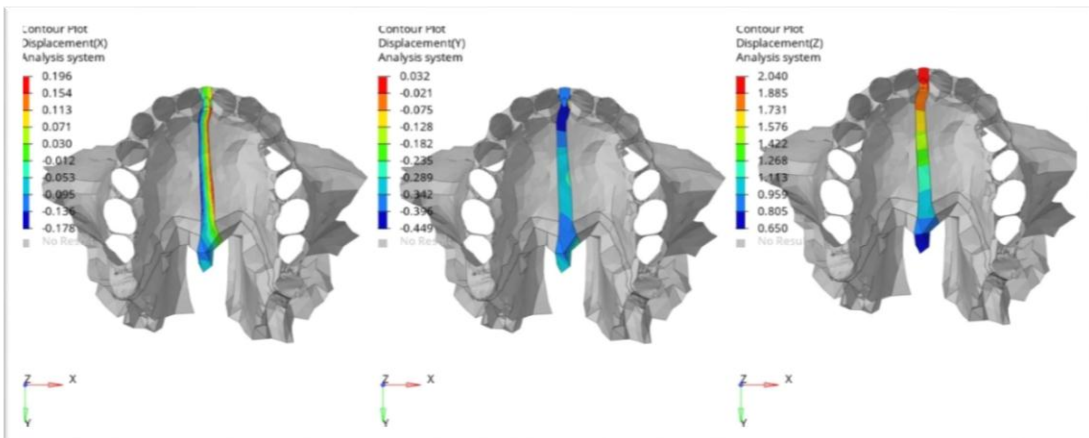

Figure 6. Displacement Contours Of Midpalatal Suture In X, Y, Z Direction

Discussion

The FEM model of the skull was generated using Mimics software and consisted of 40387 nodes and 187157elements. In this study, all the sutures of nasomaxillary complex were taken. This study applied the material property of connective tissue for all sutures. Pirelli et al. demonstrated that the periodontal ligament and the midpalatal suture have similar histological characteristics to that of connective tissue[4]. For the force application, 3-D screw was activated by giving 3 turns to the screw. 3.18 mm of expansion from lingual cusp to lingual cusp of the maxillary first molars was achieved, which helped to validate the model and force level.

The FEM simulation showed a near parallel split of the midpalatal suture and due to that Maxilla moved anteriorly and inferiorly (Fig. 3) with 3-D screw appliance in sagittal and vertical planes. (Table: 3). 1mm more of expansion was seen in the anterior ANS region when compared to the posterior. Wertz et al[5], Iseri et al[6], Jafari et al[7] in their studies stated the same thing that the maxilla moved antero-inferiorly with RME. Wertz stated that the separation of maxillary complex from the pterygoid process could allow significant anterior movement of the maxilla. In this study, Maximum Von-mises stress was around 133.78MPa in the region of canine and premolar on both the side in the maxilla (Fig. 4, Table: 4). Finding of this study was the presence of high stress all along the maxillary bone, radiating upward to deeper anatomic structures.

Lateral part of Nasal bone moved posteriorly in sagittal direction, inferior in vertical direction and lateral in transverse direction (Table: 3). Gautam P et al[8], Jafari A et al[7], Iseri et al.[6] said that the movement of the lateral nasal walls and inferior movement of the nasal floor could cause a reduction in the airway resistance. Maximum Von-mises stress was around 72.74MPa in the lateral part of the nasal bone (Table: 4). Zygomatic bone had a forward and lateral displacement. The forward displacement was minimal as a whole, whereas the lateral displacement was more near the zygomatico-maxillary suture and gradually decreased towards the temporal process of the zygomatic bone (zygomatic arch) and further decreasing towards the fronto-zygomatic suture. Overall, this zygoma rotated along with the zygomatico-maxillary complex with fronto-zygomatic suture as the fulcrum. Canteralla et al[9] in his clinical trials, saw a negligible increase in the upper inter-zygomatic distance whereas the lower inter-zygomatic distance was more which is similar to this study. They elucidated that the zygomaticomaxillary complex rotated outward with a centre of rotation located near the fronto-zygomatic suture.

The maximum stress generated in this region was 2.65 MPa with principal stress showing a compressive stress of −0.053 MPa in case of 3-D screw model (Fig. 5). Stresses at the midpalatal suture remained high in comparison to another sutures (Table: 4). Higher stress concentration was seen on the posterior part of the midpalatal suture with the decreased stresses at the anterior segment. Earlier literature also supported this finding[8]. Reason behind the high stress on the midpalatal suture can be attributed to the vicinity of the applied force, which was nearer to the suture. Anterior and upward displacement of the midpalatine suture was observed in this study (Fig. 6). As stated in the previous studies, the

separation of the sutures was pyramidal, with the base of the pyramid located at the oral side in the vertical plane and anteriorly along the antero-posterior plane for RME. Similar pattern of the opening was noticed in the present study with 3-D screw. As the maxilla is attached to the sphenoid bone through the pterygo-maxillary fissure, this kind of pyramidal opening is bound to occur[10-12].

In this study, the naso-frontal suture displaced in medio-Postero-inferior direction but to a lesser extent. Similar results were noted in the earlier studies on RME[13,14,15]. The stresses produced in fronto-nasal suture is lesser than the midpalatine, frontozygomatic and zygomaticomaxillary suture. Jafari et al maximum stress was seen in the zygomatico maxillary suture[7]. As the suture is away from the site of application of the force, the stresses produced are also less in comparison to the other sutures. The displacement of frontozygomatic suture was in lateral-antero-inferior direction (table: 3). The reason behind this less displacement in fronto-zygomatic suture is increased digitation and rigidity. The maximum stress generated in this region was 1.66 MPa with principal stress showing a compressive stress of −0.135 MPa (table: 4). Jafari et al[7] and Iseri H et al[6] stated that the more stresses were seen with this suture and this statement support this study result. All these varying patterns of the stresses are due to the fact that the absolute level of the induced stresses greatly depends on bone elasticity and the patient's age.

The intranasal suture in 3-D screw exhibited a displacement pattern in medio-Postero-superior direction at the posterior surface of the suture, suggesting of a wedge-shaped opening in the nasal cavity causing the widening of the same. Isère et al[6] also reported medial displacement of the posterosuperior part of the nasal cavity. This is in agreement with the findings of Pavlin and Vukicevic who showed medial movements of the nasal process of the maxilla and other superior structures. The maximum stress generated in the 3-D screw was 0.653MPa. The stress pattern remained uniformly tensile in this study. Results of this study were in agreement with the findings of earlier studies done by Jafari et al[7] and Gautam P et al[8].

In one of the studies on the effects of RME, there was a significant increase in the width of the naso-maxillary suture and there was a difference of 0.4 mm in the pre and posttreatment CT scans[18], but it was not true in this study as a maximum displacement of 0.551 mm was noted in the transverse plane. (Table: 3). The stresses generated by the models for the nasomaxillary suture were concentrated laterally toward the infra-orbital region. The force applied by the 3-D screw was transverse in nature. Owing to this, all the sutures move away from the midline and the greater stress was seen on the lateral wall of the naso-maxillary suture.

Zygomatico-temporal suture produced a medio-Postero-inferior displacement. The difference in the pattern of opening can again be attributed to the site of application of force. Zygomatico temporal suture was displaced lesser than the pterygomaxillary, zygomaticomaxillary and frontozygomatic sutures (Table: 3). Same has been stressed in the study of Gautam et al[8]. Maximum von mises stress was 1.25MPa (Table: 4). lateral stresses mainly radiated to the zygomaticotemporal and the sphenozygomatic sutures and it has been

demonstrated that the pattern of stress distribution was different along the various craniofacial sutures in response to RME. Both tensile and compressive stresses of variable magnitude were demonstrated along the same suture.

The maximum displacement pattern at pterygomaxillary suture showed medio-antero-superior direction (Table: 3). One has to remember that the sutures are not opening up in a uniform manner at all the nodes & not in a parallel manner; because of this, the results are noticed in a varying pattern of negative and positive values. The stress pattern was tensile in nature. The literature related to stress pattern for this particular suture remain scanty. As pterygo-maxillary suture is nearer to the midpalatal suture, the stresses generated are greater. But in this study the stresses are lesser than the other sutures. The zygomatico-maxillary suture in this study displaced laterally and Antero-superiorly, resulting in a wedge-shaped splitting of the maxilla along with a downward displacement thus, producing a similar displacement pattern on the zygomatic bone (Table: 3). Contrasting results were seen in the study of Ghonemia et al. who showed an insignificant change in the width of the suture. However, there were other studies which did not support the present study results[4]. Maximum Von-mises stress was around 3.62MPa & Compressive stress of around 0.65MPa was observed (Table: 4). Jafari et al stated that maximum stress was seen in the zygomatico maxillary suture, frontal process of zygoma, zygomatic arch and zygomatico temporal suture[7].

All the teeth moved buccally. Maximum displacement occurred in posterior teeth on both the side (Table: 3). Maximum Von-mises stress was around 126.85MPa at the CEJ of first premolar (Table: 4). Iseri et al. observed large amounts of stress accumulation in the canine and molar areas in the maxillary arch[6]. Maximum Von-mises stress was around 39.6MPa in the alveolar bone in the region of central incisors. The lingual alveolar bone showed superior displacement on the Z axis in the central incisor area. Displacement and stress were calculated after giving 3 turns to the screw, the von Misses stresses developing in the craniofacial skeleton have been found 133 MPa which were considered normal yield strength (130 MPa) of the bone (Kayabasi et al., 2006)[16]. Here only 3 turns were given because if more than 3 turns were given then there was increase in the stress or yield strength which makes this study less reliable to be used in any clinical situation.

Conclusion

Pyramidal displacement of maxilla was evident. Apex of pyramid faced the nasal bone and base was located on the oral side. There was downward, forward movement of maxilla with a tendency toward posterior rotation. Maximum von Mises stresses were found along midpalatal, zygomaticomaxillary, nasomaxillary, frontozygomatic sutures. This study also conclude that the distant structures of the craniofacial skeleton were also affected by transverse orthopaedic forces. In this study, there was transverse as well as anterior expansion achieved with 3-D screw, which cannot be achieved with any slow or rapid maxillary expansion device. So, 3-D screw is appliance of choice to treat antero-posterior as well as transverse discrepancy simultaneously in the growing individual with skeletal class III malocclusion.

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